Acceptance limits for the duration of pre-Helmholtz transients in bowed string attacks

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The attack of most bowed notes shows an initial part before Helmholtz triggering occurs (the *pre-Helmholtz transient*), during which the stick-slip interaction promotes frequencies other than that of the string's fundamental. Depending on the particular combination of bowing parameters, this state is characterized either by periods that are *prolonged*, or by a division of the period into two or more parts, *multiple flyback*. An onset with perfectly periodic motion (Helmholtz triggering) directly from the very start is also possible. A sample of violin tones representing these three classes of attacks, and with different duration of the pre-Helmholtz transient, has been collected by the use of a computer-controlled bowing machine. The tones were evaluated by 20 advanced string students and professionals in a listening test, judging the acceptance and quality of the attacks. The maximum acceptable duration of the pre-Helmholtz transient was estimated to 50 ms ($\leqslant$10 nominal periods, open G string, violin) for attacks with prolonged periods, and 90 ms ($\leqslant$18 periods) for multiple-flyback attacks. These values refer to a neutral start in a neutral context, such as when practicing a scale. A playing test, in which the performances of two professional violinists were analyzed, confirmed these results, and showed that the same limits apply to a larger group of bowing styles as well. [S0001-4966(97)05504-5]

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INTRODUCTION

The attack of a note on a bowed instrument shows a transition phase during which the ''steady-state'' motion develops. In particular, the stick-slip interaction often starts with an aperiodic initial part before Helmholtz triggering occurs and the fundamental periodicity is established. This is so because the conditions for a ''perfect attack,'' where the string slips under the bow hair only once per fundamental period from the very beginning of the note, are too demanding to be met in practice at each stroke.

Depending on the actual combination of bowing parameters, the initial part of the attack is characterized either by periods which are *prolonged* (sometimes referred to as ''delayed triggering''), or by a division of the period into two or several parts, *multiple flyback*,[1] or ''multiple slip'' (see Fig. 1). As will be shown, roughly half of the attacks in a normal string performance will be either one of these two types. An attack with perfectly periodic motion (Helmholtz triggering) directly from the very start is also possible, being the standard reference of an ideal attack in string playing.

An attack with prolonged periods will normally be perceived as ''choked/creaky,'' while a multiple-flyback attack will be characterized as ''loose/slipping.'' However, provided that the aperiodic states do not last too long, such attacks could very well pass as acceptable. *How long* has been a matter of discussion, but professional string players claim that the transient must be short, the attack should sound ''clean.''

The main question addressed in this study was: ''How long aperiodic attack transients (before the triggering of the periodic Helmholtz motion) do professional string players accept for notes with a neutral attack in a neutral context?'' Such a reference would be useful when analyzing the bowed string, either through computer modeling, or from observations on real strings.

It is to be noted that even notes with a perfect Helmholtz motion from the very beginning show a transient state during which the amplitude develops and subfundamental frequencies are excited, among other phenomena. In particular, the time for reaching final ''steady-state'' amplitude, the *amplitude buildup time*, is an important characteristic of a bowed attack. The main aspect of the transient state treated in this study is, however, the duration of the aperiodic part before the triggering of the Helmholtz motion. In the following, this state will be referred to as the *pre-Helmholtz transient*.

The study was divided into two parts: (1) a listening test, in which a large group of string players judged the acceptance of recorded bowed attacks, and (2) a playing test, in which the performances of two professional violinists were analyzed.

I. LISTENING TEST

A. Recordings

A series of bow strokes on the open G string of a violin (G_3=196 Hz) was recorded on a DAT recorder, using a computer controlled bowing machine.[2] One channel recorded the string velocity at the bowing point (later used for evaluating the stick-slip action),[3] while the other channel was fed with

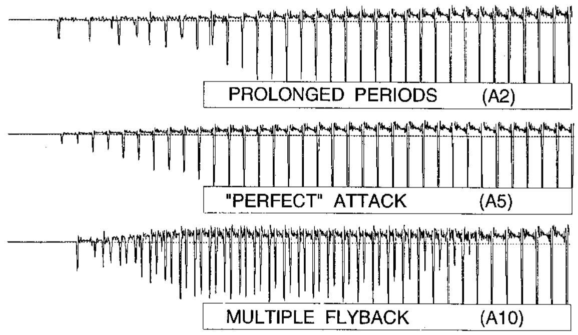

FIG. 1. Measurements of the string motion on a violin illustrating the three principal types of bowed string attacks. String velocity at the bowing point for prolonged (*top*), ''perfect'' (*middle*), and multiple-flyback attacks (*bottom*). The notes were played with a bowing machine using a normal bow. The time window shown is 200 ms and the nominal period 5.1 ms (open G string). Notice the accented onset of the multiple-flyback attack (A10).

the signal from a small electret microphone inside the violin. All strokes were run with a bow-bridge distance of 28 mm (relative bowing position $\beta=1/11.6$), and a constant bow force of 800 mN. The amount of rosin on the bow (and thus the frictional properties) was varied from stroke to stroke. Different strokes were programmed on the bowing machine, each starting from rest and accelerating according to a predetermined value up to a steady velocity of 20 cm/s.

A selection of attacks was made, resulting in a series of bow strokes representing *perfect* attacks, and *prolonged* and *multiple-flyback* attacks of different durations. The microphone recordings of these notes were transferred to a digital sound editing program,[4] by which they were normalized to equal durations (1000 ms) and decay times (300 ms). A modest reverberation and equalization were then added in order to mimic a normal violin sound (as perceived by the performer), as closely as possible.

B. The series of attacks

Eleven attacks were chosen to represent a reasonable spread in transient behavior, ranging from 160 ms of prolonged periods to 200 ms of multiple flyback periods before the occurrence of Helmholtz triggering (see Table I, Series A, violin). In order to study whether or not an accent would influence the perceived quality of an attack, copies of two of the selected attacks (A5 and A11) were artificially accented and added to the series (with an X added to the name), giving 13 attacks in all. The envelope of the artificial accents boosted the initial period by 12 dB, followed by a smooth decay covering 5–6 periods down to the original level. Of the six multiple-flyback attacks, two had pronounced natural accents (A8 and A10, the latter shown in Fig. 1).

A second series was derived from the first by changing the sampling rate (see Table I, Series B, ''viola''). For series B, the pitch was lowered a fifth from 196 Hz corresponding to the open G string of the violin, to 131 Hz, which would compare with the open C string on the viola. This series was referred to as ''another string instrument'' when presenting the sound examples in the listening test, avoiding a direct reference to the viola. The second series was normalized and equalized similarly to series A.

The buildup time for reaching final string amplitude was measured with a sound file editor,[4] observing both the string velocity and the sound track. The buildup time was measured from the first flyback to a point where the amplitude had reached 90% (−1 dB) of the ''steady-state'' level. The attacks in the series were chosen primarily on the basis of the

TABLE I. Data for the two series of attacks in the listening test. Series B (''viola'') was obtained from Series A (violin) by lowering the sampling rate to 2/3. **Attack characteristics** indicates the type of stick-slip pattern. **Bow acc.** gives the programmed acceleration of the bow. Each stroke started with the bow at rest and accelerated to a steady velocity of 20 cm/s. **Buildup time** indicates the time for reaching 90% (−1 dB) of final ''steady-state'' amplitude, counting from the first flyback. Different amounts of rosin were used on the bow, which explains the inconsistency between bow acceleration and buildup time. **Pre-Helmholtz** gives the duration of the pre-Helmholtz transient, counting measured in absolute time [ms] and nominal periods [T_0] (violin 5.1 ms; ''viola'' 7.7 ms). Asterisks indicate attacks with pronounced accents. An X added to the name indicates that the attack was accented artificially (see text). **Answer Yes** refers to the question: ''Does the attack sound acceptable?'' in the listening test. Attacks achieving more than 50% acceptance are indicated by bold print and shading. The values are based on the answers from 20 subjects×3 repetitions=60 answers per attack.

Attack characteristics		Bow acc.	Series A violin					Series B ''viola''				
			Attack name	Buildup time	Pre-Helmholtz		Answer Yes	Attack name	Buildup time	Pre-Helmholtz		Answer Yes
Type	Accent	cm/s²		ms	ms	T_0	%		ms	ms	T_0	%
Prolonged		40	A1	420	160	31	0	B1	630	240	31	0
Prolonged		100	A2	180	55	11	35	B2	270	83	11	8
Prolonged		125	A3	130	30	6	**77**	B3	200	45	6	47
Prolonged		100	A4	170	20	4	37	B4	260	30	4	23
Perfect		150	A5	120	0	0	**92**	B5	180	0	0	**78**
Perfect	*	150	A5X	120	0	0	**92**	B5X	180	0	0	**82**
Mult. flyback		150	A6	130	15	3	**93**	B6	200	23	3	**78**
Mult. flyback		300	A7	70	40	8	**90**	B7	110	60	8	**87**
Mult. flyback	*	200	A8	90	60	12	**80**	B8	140	90	12	38
Mult. flyback		150	A9	130	90	18	**52**	B9	200	135	18	48
Mult. flyback	*	500	A10	140	140	27	30	B10	210	210	27	38
Mult. flyback		150	A11	200	200	39	12	B11	300	300	39	7
Mult. flyback	*	150	A11X	200	200	39	17	B11X	300	300	39	33

duration of the pre-Helmholtz transient, but as will be shown later, also accents and amplitude buildup time played important roles in the judgment of attack quality.

C. Design and procedure

The two series of attacks were evaluated in a listening test by a panel of 20 advanced string students and professionals at the Norwegian State Academy of Music. The recorded attacks were presented to the test panel in a medium sized auditorium at a moderate sound level, using a single loudspeaker.

Three sequences were played, each consisting of 26 attacks. Each attack was repeated three times in quick succession, followed by 10 s of silence, which allowed for writing down the scores. In the first sequence, the 13 attacks of series A appeared twice in random order. The next sequence was composed in an equal manner from series B, while in sequence three, series A and B were scrambled. The subjects thus judged each attack three times during the test session, which allowed an estimation of the intraindividual reliability. For each attack, three scores were given:

(1) **Acceptance**. The acceptance of the attack was indicated by answering the question: ‘‘*Does the attack sound acceptable?*’’ with ‘‘Yes’’ or ‘‘No.’’

(2) **Quality**. The quality of the attack was indicated on a line (100-mm long) with the end points defined as: ‘‘*The attack is catastrophic*’’ and ‘‘*The attack is perfect.*’’

(3) **Character**. The character of the attack was indicated on a line (100-mm long) with the end points defined as: ‘‘*The attack sounds extremely choked/creaky*’’ and ‘‘*The attack sounds extremely loose/slipping*’’ with the midpoint indicated by ‘‘*without creaks or slips.*’’

The participants were instructed to judge the attacks with reference to a ‘‘neutral attack,’’ for example as when practicing a scale. For Quality and Character, the positions of the marks (measured in millimeters) were taken as the score values, thus ranging from 0 to 100.

Before the actual listening test started, two extreme examples of attacks with very long pre-Helmholtz transients were presented, in order to illustrate the two contrasting types of attacks (prolonged and multiple flyback) and establish the terminology. Being professional string players and students, the subjects could be assumed to be familiar with the phenomena *per se*. Following, all 13 attacks of series A were played in quick succession. Finally, the subjects judged four other attacks in a training session, in order to become familiar with their task.

D. Results

1. Acceptance

A first estimation of the acceptance limits for the duration of the pre-Helmholtz transient was obtained from the answers to the Acceptance question: ‘‘Does the attack sound acceptable?’’ Table I gives the percentages of approvals with a total of 60 answers per attack. Using a lower limit of 50% ‘‘Yes’’ as a reasonable *ad hoc* criterion of acceptance, the maximum acceptable duration of the pre-Helmholtz transient for the violin attacks can be estimated to 30–50 ms on the prolonged side, and around 90 ms on the multiple flyback side. (The poor rating of attack A4 will be discussed in Sec. I D 3.)

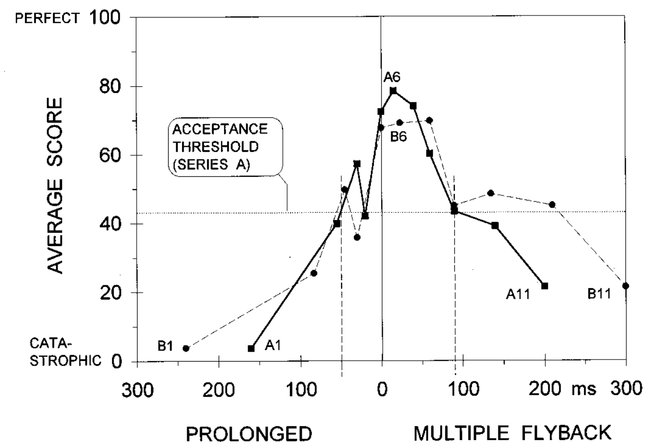

FIG. 2. Judgment of the Quality of the attacks. Averaged scores across 20 subjects for two series of attacks (series A, violin, *solid line*; series B, ‘‘viola,’’ *dashed line*). The scores for the artificially accented X versions are not included. The figure shows that attacks with a short duration of the pre-Helmholtz transient are preferred. A calculated threshold of acceptance for series A (43 units) is included for reference (*horizontal dotted line*). Estimated acceptance limits for series A are shown at 50 ms of prolonged periods and 90 ms of multiple flyback (*vertical dashed lines*). Interestingly, the data indicate a greater tolerance for multiple-flyback attacks than for attacks with prolonged periods (see text).

For the ‘‘viola’’ attacks, the acceptance limits seemed shorter, 60 ms on the multiple flyback side, and with no tolerance at all for prolonged-period attacks (0 ms). A strict application of the rough acceptance limit may, however, be slightly misleading in this case, taking into account that attacks B3 (prolonged, 45 ms) and B9 (multiple flyback, 135 ms) just barely fell below 50% acceptance.

2. Quality

The Quality scores for series A and B, averaged across subjects, are shown in Fig. 2, with the prolonged period and multiple-flyback cases arranged mirror symmetrical around the perfect case. When plotted in this manner, the abscissa corresponds (qualitatively) to the continuous progression in bowing parameters from high bow force and low acceleration (prolonged, left), to low bow force and high acceleration (multiple flyback, right).

The score values form a bell-shaped distribution. As expected, the attacks with the highest acceptance are those with a short pre-Helmholtz transient. The peak in the score distribution was, however, not located at zero duration (perfect attack) but rather at about 15–25 ms (3–5 nominal periods) of multiple flyback. This bias, as well as the influence of artificially introduced accents, will be discussed below (Secs. I D 3 and I D 4).

The attacks were classified as accepted or rejected by introducing a threshold of acceptance in the score distribution (see Fig. 2). The threshold was estimated to be 43 units for series A (violin) on the rating scale for quality ranging from 0 (‘‘catastrophic’’) to 100 (‘‘perfect’’). This value was found by arranging all quality scores for series A in a descending array and selecting the Mth element, where M is the total number of *accepted* attacks for series A according to the acceptance judgment above (Sec. I D 1). It would then be expected that a majority of the listeners would judge a violin attack with an average score of less than 43 units as ''not acceptable,'' and vice versa. Using this definition, all prolonged-period attacks shorter than approximately 50 ms (10 nominal periods) were judged as acceptable (excluding attack A4). The corresponding limit for the multiple-flyback attacks was 90 ms (18 periods).

The same approximate limits in absolute terms (ms) seem to apply to series B (''viola''), taking into account that the acceptance threshold for this series was 51 units. In this case, the 50- and 90-ms limits correspond to only 7 and 12 nominal periods for the prolonged and multiple-flyback attacks, respectively. Some precaution in the interpretation of these results may be necessary, however, as the ''viola'' examples were artificially derived from the violin attacks. It can be noted in passing that the scores outside the acceptance limits dropped steeper for the violin than for the ''viola,'' possibly indicating a lower sensitivity to poor ''viola'' attacks.

As expected, the classification of the attacks as accepted or rejected with the aid of the computed threshold gave essentially the same result as the answers to the Acceptance question, except a slight widening of the acceptance range for series B.

The acceptance limits for the duration of the pre-Helmholtz transient given above form a major result of the study. Following, some particular conditions will be discussed which may have influenced the judgments.

3. Influence of bow acceleration and amplitude buildup time

The bow acceleration and the resulting time for reaching final ''steady-state'' amplitude (amplitude buildup time) are important for the rating of the quality of an attack. A short buildup time is rated favorable. Two observations illustrate this dependence.

The shift of the peak in the score distribution towards attacks with some multiple-flyback periods (see Fig. 2) is most likely explained by the amplitude buildup time. Two effects seem to combine in this case: (1) A small amount of multiple flyback (15–25 ms) is probably not perceived as disturbing, being masked by the following stronger part of the note; (2) The relatively high acceleration of the bow (which is the primary cause of the multiple flybacks) will force the string to accelerate fast as soon as it has been securely caught by the bow and a regular Helmholtz triggering sets in, giving a short buildup time. Altogether, these two effects can give the impression of a fast and clean attack, which probably explains why the short multiple-flyback attacks A6 and A7 were rated the highest, in preference to the perfect attack.

Also the dips in the averaged score distribution in Fig. 2 are most likely connected with the amplitude buildup time. In particular attack A4 (20 ms, prolonged), and the corresponding ''viola'' attack B4 (30 ms, prolonged) obtained low ratings. The explanation here would be that attack A4

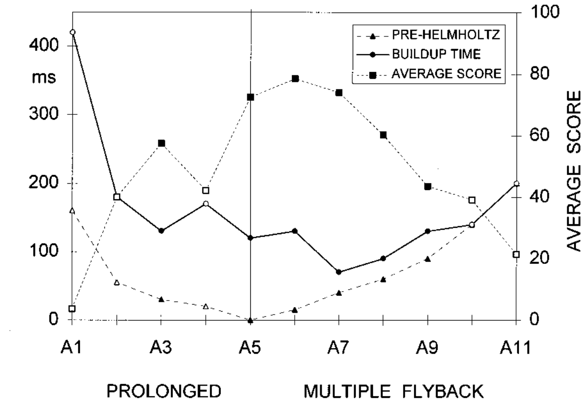

FIG. 3. Comparison between the duration of the amplitude buildup time (*solid line*) and the pre-Helmholtz transient (*dashed line*). The average scores for series A from Fig. 2 are included for reference (*dotted line*). Accepted attacks (above the acceptance threshold in Fig. 2) are shown with filled symbols.

was played with lower bow acceleration than the preceding attack in the series (A3), thus giving longer buildup time (200 ms compared to 160 ms, see Table I). Logically, A4 should have been recorded with a higher bow acceleration than A3, but as mentioned, attacks of suitable duration of the pre-Helmholtz transient were collected by changing the bow acceleration, or friction characteristics, or both.

At this point it is appropriate to ask whether the subjects actually rated the duration of the pre-Helmholtz transient, or rather the amplitude buildup time. A comparison between the buildup time and the duration of the pre-Helmholtz transient shows, as expected, that they are related (see Fig. 3). On the prolonged side, the buildup time was long due to a low bow acceleration (between 420 and 130 ms), and always much longer than the pre-Helmholtz transient. For the perfect attack with no pre-Helmholtz transient (A5) the buildup time was 120 ms. The minimum in buildup time (70 ms) was found a little in on the multiple-flyback side (A7, 40 ms multiple flyback), next to the attack with peak scores (A6). For the longest multiple-flyback attacks (A10, A11) the buildup time equaled the duration of the pre-Helmholtz transient (140 and 200 ms), simply because the bow reached its final velocity before a safe grip of the string had been established.

A comparison between the Quality-score distribution and the buildup times shows clearly that the buildup time alone cannot have served as the basis for the judgment (see Fig. 3). If that were the case, multiple-flyback attacks would have obtained much more favorable ratings in general, as the shortest buildup times were found in this region. In particular, there are no reasons to expect that an acceptance limit in buildup time would be different on the prolonged and multiple flyback side. But in this test, attacks with the same or comparable buildup times were rated quite differently. Three attacks with the same buildup time (130 ms) give a striking illustration. The prolonged-period attack (A3) was gladly accepted, the attack with a short multiple-slip transient obtained peak scores (A6), while the long multiple-flyback attack (A9) was at the threshold of being rejected.

From this digression it is clear that it is the duration of the pre-Helmholtz transient which serves as the main parameter when judging the acceptance of bowed attacks. A desire for short buildup times bias the judgments towards attacks with a slight amount of multiple flyback (peak scores for attack A6 with 15 ms of multiple flyback). A lengthening in buildup time relative to adjacent cases is immediately reflected in lowered scores (e.g., A4 and A9). Even the attack with peak scores (A6) would probably have been rated still higher, had the buildup time been more in line with the adjacent attacks.

From the player's point of view, a desire for short buildup times means that some of the perfection in the initial Helmholtz triggering may be sacrificed in favor of a shorter buildup time. With this in mind, somewhat excess bow acceleration is safer than too little. All attacks above the acceptance threshold in Fig. 2 had amplitude buildup times shorter than 130 ms (series A), but this value should not be interpreted as an indication of the lower limit in general. In real music performance, a variety of bow accelerations are required and a correspondingly large variation in buildup times will be accepted. When practicing scales and clean attacks, however, the musician is in general striving for the quickest possible response from the instrument, which would explain the preference for short buildup times in the listening test.

4. Effect of accents

The effect of (artificially introduced) accents seemed to be dependent on the quality of the attack. The two artificially accented attacks A5X and B5X, both being perfect attacks with no pre-Helmholtz transient, were rated very similar to their unboosted originals as regards Acceptance (see Table I). The difference in average rating of Quality was only one score unit (1% of rating range) approximately, also indicating a very small perceptual difference.

On the other hand, for attacks with a long multiple-flyback transient as A/B11X (200/300 ms) the introduced accents were perceived as a major improvement by a majority of the listeners. For these attacks, the averaged quality scores increased by 10 and 20 units, respectively, compared to the originals. A possible explanation of this effect might be that an accent gives the impression that the bow has a better grip of the string than is actually the case.

5. Character

The scores for Character for series A and B, averaged across subjects, are shown in Fig. 4. The figure shows that there is a clear relation between the type of string motion during the attack and the perceived character. Attacks with prolonged periods are perceived as ''choked/creaky,'' while multiple-flyback attacks are referred to as ''loose/slipping'' (with a few exceptions).

Again, accents seem to play an important role, now for the classification of an attack as being of one or the other type (cf. Sec. I D 4). The data in Fig. 4 show clearly that any accent is interpreted in the direction of ''choked/creaky,'' as illustrated by the lowered score values of A/B 5X and 11X, to which artificial accents had been added. In particular, a remarkable shift in rating was observed when an accent was added to the long multiple-flyback attack B11. The average score changed from 85 (corresponding to something like ''very loose/slipping'') to 48 for B11X (''without creak or slip''). This shift in perceived quality is even more surprising when considering that the duration of the accent corresponded to a few nominal periods only.

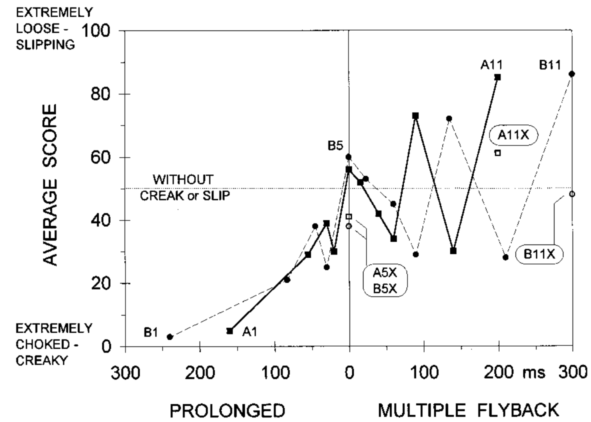

FIG. 4. Judgment of the Character of the attacks. Averaged scores across 20 subjects for the same two series of attacks as in Fig. 2 (series A, violin, *solid line*; series B, ''viola,'' *dashed line*). The scores for the artificially accented X versions are marked separately. The figure shows that attacks with prolonged periods are generally characterized as ''loose/slipping,'' while multiple-flyback attacks are judged as ''choked/creaky.'' Accented attacks tend to be perceived as choked/creaky (see text).

The scores on the multiple flyback side in Fig. 4 appears to be less systematic than those on the prolonged period side. In particular, the low scores for attacks A/B 8 and 10 (indicating a ''choked/creaky'' character) upset the picture. Here too, the explanation is probably connected with accents. In both series, attacks A/B 8 and 10 had (natural) accents, and attacks A/B 6 and 7 sounded accented as well, although by far not as pronounced.

The multiple-flyback examples discussed above and the profound influence of accents clearly illustrate that even advanced string players may have difficulties in classifying bow attacks into the proper categories. A correct classification is necessary, however, in order to be able to adjust the bow acceleration or bow force, if the player is striving for a perfect attack. Although the task is difficult, a player will be in a slightly better position than the subjects in the listening test (or a teacher) when deciding which corrections should be made. Experience tells that, in real playing, a good deal of information on the bow-string interaction can be perceived through the bow and fingertips as a result of the high and rapidly changing frictional forces during the attack.

E. Statistical analysis

1. Analysis of variance

The ratings from the listening test were analyzed by means of analysis of variance, using a mixed model with ''Attacks'' as a fixed factor and ''Subjects'' as a random factor (see Table II). This choice of model would allow a generalization of the result of the listening test to represent the opinion of a large population of string students and professionals.

TABLE II. Summary of analysis of variance of the pooled scores for Quality and Character for series A (violin) and B (''viola''). The artificially accented attacks (X attacks) were not included in the analysis.

QUALITY Source of variation	df	MS	F value
Attacks (A)	21	28210	55.97[a]
Subjects (S)	19	6004	20.49[a]
Interaction (A×S)	399	504	1.72[b]
Within cell (*w*)	880	293	
CHARACTER Source of variation	**df**	**MS**	**F value**
Attacks (A)	21	31611	117.51[a]
Subjects (S)	19	12570	7.22[a]
Interaction (A×S)	399	269	1.55[b]
Within cell (w)	880	174	

[a] $p<0.001$.
[b] $p<0.01$.

A preliminary inspection of data showed that the artificially accented attacks (X attacks) confused the subjects in their judgments. A plausible reason would be that these attacks sounded artificial in the word's literal meaning (''lacking in natural quality''), and hence was not possible to rate with reference to the subjects' experiences as string players. Whatever the cause, these attacks were discarded from the subsequent analyses.

The analysis of variance showed, as expected, that there were significant differences in average scores between the attacks, both in Quality and Character (see Table II, factor A). A nonsignificant result in this factor would have been very disappointing as the attacks were carefully chosen to represent a wide spread in these respects. Further, there were significant differences between the ratings given by different subjects (S), meaning that the subjects used different parts of the rating scale.

A more interesting question is whether the *differences* (in average scores) between the attacks were the same or not for different subjects, regardless of the subjects' mean position on the rating scale. As seen in Table II, the (A×S) interaction was significant, which means that the differences between the mean ratings of individual attacks were not similar for all subjects. This fact is by no means alarming in itself, as will be discussed in Sec. I E 3 (''percent of variance accounted for''), but it illustrates that the subjects did not quite agree upon how much the attacks differed.

The subjects did agree on the *ranking* of the attacks, however, as shown by a rank correlation test.[5] This test checked whether the subjects ranked the attacks in the same order, with no attention paid to the score magnitudes. The result of this test was highly significant ($p<0.001$).

All results and conclusions for Quality scores given in this section apply to the Character scores as well (see Table II).

2. Intra-individual reliability

The intra-individual reliability, or the consistency of the ratings within each subject, was checked by calculating a

TABLE III. Percent of variance accounted for by different sources.

Source	Quality	Character
Attacks (A)	50	70
Subjects (S)	9	2
Interaction (A×S)	7	4
Error (''within cell'')	34	24

''Reliability index for individual subjects'' (r_w).[6,7] An interpretation of this measure would be that if the listening test was repeated with the same subject under the same conditions, the correlation between the mean ratings for the individual attacks in the two tests would be approximately r_w. As a rule of thumb, subjects with r_w above 0.50 can be considered as acceptable in a listening test.

In addition, the error variance for each subject $MS_{\text{within cell}}$ was calculated. This measure indicates how much a subject varies in repeated ratings of the same attack during the test. An approximate upper limit for MS_w would be 150 units squared $\approx$ (12 units)^2 (Ref. 6).

All subjects showed a satisfactory reliability in their judgments according to the two measures above. For the Quality (Character) scores, 11 (15) subjects out of 20 had a reliability index above 0.90, the lowest being 0.75 (0.85). The median of the MS_w values was 59 (25).

3. Inter-individual reliability

The inter-individual reliability, or the agreement between the ratings given by different subjects, was estimated by a ''Reliability index between subjects'' (r_B).[7] This index has a powerful interpretation which makes it particularly informative. If the listening test was to be repeated with another random sample of 20 subjects from the same population (advanced string students and professionals), the correlation between the mean ratings for the individual attacks in the two tests would be approximately r_B. In the present case, r_B turned out to be as high as 0.99 both for Quality and Character, which indicates an excellent agreement between subjects, and consequently a high reliability of the mean ratings presented in Fig. 2. A very similar result would have been obtained with another sample of subjects.

Still more information on the reliability can be obtained from a calculation of how much of the variance in the subjects' data is accounted for by different sources (see Table III).[7,8] These calculations revealed that by far the largest part of the total variance in the ratings, 50% for Quality (70% for Character), can be attributed to differences between the attacks. A sequential analysis of the averaged ratings showed no appreciable learning effects between the first and third rating of the same attack.

A closing remark on the subjects' task might be appropriate. It can be argued that the sound generated in such a complex process as a bowed attack must be related to several perceptual dimensions, and a straightforward judgment in one or two parameters may not be meaningful. Before the listening test started, some subjects actually expressed concerns about summarizing the quality of an attack in a single rating. Reference was given to the many different ways of

FIG. 5. Music used in the playing test, representing different styles of bowing. (a) A simple tune ''Twinkle, twinkle, little star,'' *tenuto-détaché-martellato*, performed in tempo M.M.=100–110 beats/min; (b) Theme from Beethoven's violin concerto, Op. 61, *tenuto*, M.M.=93; (c) Excerpt from Preludio V from Das Wohltemperierte Klavier by J. S. Bach, *détaché*, M.M.=60; (d) Theme from L'Arlésienne suite by Bizet, *martellato*, M.M.=110; (e) Theme from Wilhelm Tell overture by Rossini, *ricochet*, M.M.=125. All examples were performed both on the G string as shown, and on the E string transposed an octave plus a major sixth.

starting notes which are used in contrasting musical contexts. Their concerns faded away, however, as soon as the introductory sound examples were presented, indicating that a single perceptual dimension, in this experiment referred to as Quality, was possible to rate on a scale between ''Catastrophic'' and ''Perfect.''

II. PLAYING TEST

A. Method

A playing test was performed in order to study the pre-Helmholtz transients in real violin playing, in particular the distribution of transient durations. Two professional violinists performed a simple tune (the first phrase of ''Twinkle, twinkle little star'') on the G string (G major), and on the E string (E major), respectively [see Fig. 5(a)]. Three bowing styles were used; *tenuto* (''held,'' broad strokes, fully sounding through the entire note value), *détaché* (''separated,'' articulated attacks with no or little release of bow force between notes), and *martellato* (''hammered,'' very pronounced attacks, anticipating each stroke with extra bow force and releasing the force rapidly after the onset). The 14 notes in the phrase were played at a tempo of 100–110 beats/min, using alternating up and down-bows, with one exception at which two up-bows followed in succession [see Fig. 5(a)]. Each manner of bowing was repeated four times (three times by the second performer) and at three dynamic levels ($p-mf-f$), resulting in a total of $2\times3\times4(3)\times3=72$ (54) renderings by the two performers, respectively, corresponding to 1008 (756) attacks.

A two-channel recording was made on a DAT recorder, documenting the string velocity at the bowing point,[3] and the sound pressure close to the violin (measured by a dedicated violin microphone mounted to the instrument).[9]

A fine violin of professional quality was used,[10] and both players were most satisfied with the instrument. They also assured that the minor preparations of the violin for the recording did not disturb their playing. Both players used their own bows. The players were not informed about the purpose of the experiment, but were only given the music with the instructions of bowing styles and dynamic levels and asked to perform accordingly. If a player was not satisfied with a certain rendering, this version was deleted and replaced with a new recording.

The recordings were analyzed using a sound file editor.[4] The duration of the transient state before Helmholtz triggering was measured with the aid of the string velocity signal, and the attacks were classified into three categories (*prolonged*, *perfect*, and *multiple flyback*). The criteria for classifying an attack as ''perfect'' were: (1) the string velocity signal should show a smooth buildup in flyback velocity amplitude, and (2) only occasional drops in velocity (down to zero or crossing the zero line) should take place during the nominal sticking part of the period. Minor partial slips with no dynamic consequences for the development of the tone may thus have occurred also in attacks classified as perfect.

In order to avoid ambiguous classification of ''almost perfect attacks,'' an short initial buffer zone was introduced. All attacks with an initial aperiodic transient shorter than 5 ms were classified as perfect. This leeway was particularly apt for the classification of attacks at p level. A total of 1694 out of the 1764 recorded attacks (96%) were successfully analyzed and classified.

B. Results

1. A simple tune

a. G string. The results for the simple tune played by the first subject is shown in Fig. 6, in which distributions of the pre-Helmholtz transient durations are displayed separately for the three dynamic levels, and also summarized in a pooled plot.

The figure shows, first of all, a good agreement between the actual durations of the pre-Helmholtz transients which occur in normal playing, and the limits for acceptable durations obtained in the listening test. Very few prolonged-period attacks exceed 50 ms, and attacks with multiple flyback are normally not longer than 90 ms. Between 80% and 90% of the attacks (depending on bowing style) stayed between these limits. Such an agreement is not obvious as the players in no case were instructed to play the notes with ''neutral'' attacks, which, in contrast, was the rating reference in the listening test.

Between 20% and 50% of the attacks were perfect, depending on the dynamic level and bowing style. The highest rate of perfect attacks which occurred in the experiment (79%), was observed for the second subject in martellato at p level. It is to be noted, however, that out of the 121 analyzed recordings of the tune, only *one* had all 14 consecutive attacks classified as perfect. Although such a perfect series thus seems to be rare in normal performance, informal ex-

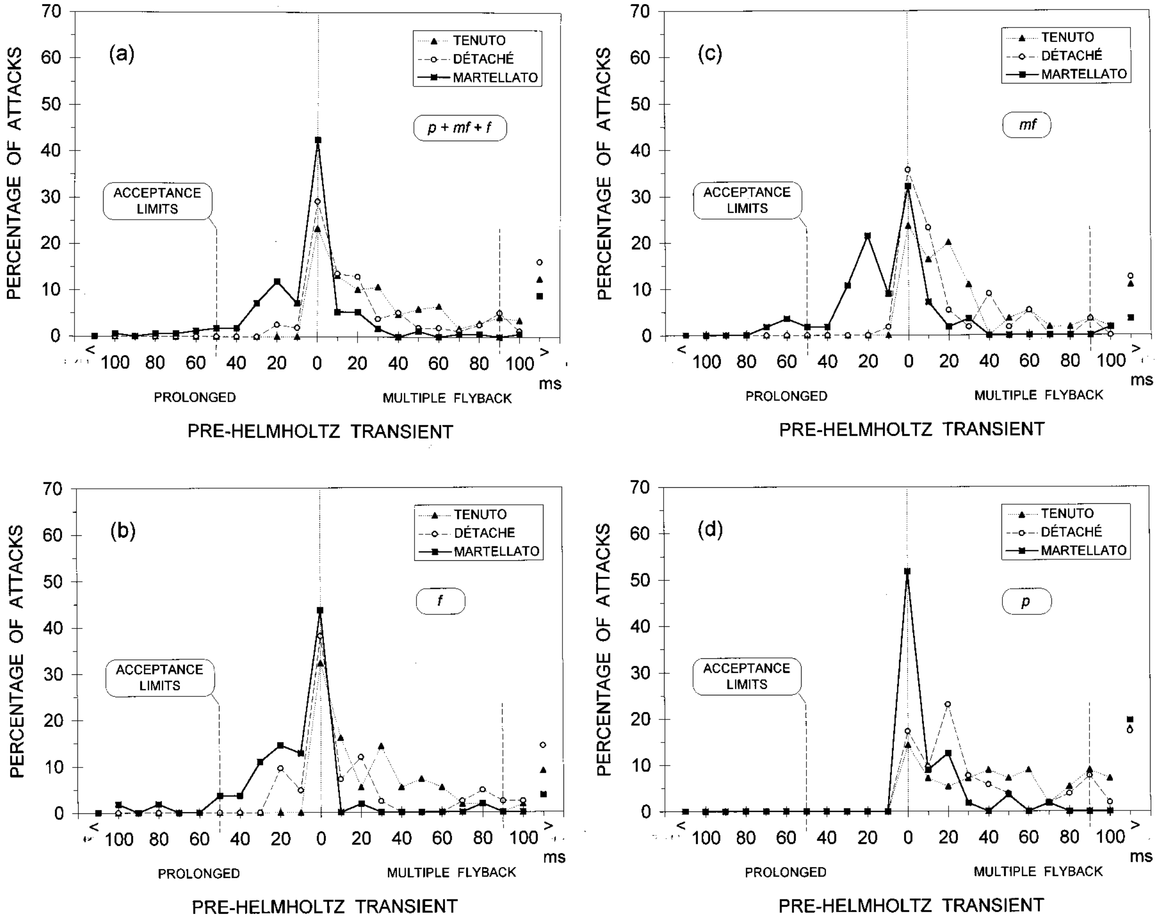

FIG. 6. Distributions of the durations of pre-Helmholtz transients in a simple tune (''Twinkle, twinkle, little star'') played on the G string using three different bowing styles (*tenuto, détaché*, and *martellato*) by one performer. (a) Pooled plot showing three dynamic levels, $p-mf-f$. Each bowing style was repeated four times at each dynamic level (with one exception) giving a total of 35 repeats, corresponding to 490 analyzed attacks. The class width is 10 ms centered around the tick mark values. Transients with durations longer than 105 ms are summarized in the outermost data points (indicated by $<$ and $>$). The acceptance limits obtained in the listening test are included for reference (*vertical dashed lines*). Separate plots of the distributions at different dynamic levels are shown in; (b) *forte* (168 attacks); (c) *mezzo forte* (154 attacks); and (d) *piano* (168 attacks).

periments showed that a professional string player can easily reproduce a sizable series of consecutive perfect attacks when concentrating on this task, for example, during a practice session.

As regards the multiple-flyback attacks, a certain amount of very long pre-Helmholtz transients were observed. These ranged between 100 and 600 ms, and would in some cases last the entire note. Even so, the perceived pitch did not deviate from the intended (by an octave or some other integer ratio), but the string spectrum showed a weak fundamental and sometimes also weak odd partials. Such notes with long multiple-flyback attacks are perceived as having a ''surface'' quality, giving associations to cautious string playing with light bow pressure rather than to a poor attack. These notes with long multiple-flyback attacks were observed preferably in tenuto and détaché, being most sustained at p level.

The influence of dynamic level and bowing style was striking [see Fig. 6(b)–(d)]. The perfect attacks showed the highest rate for all bowing styles at all dynamic levels. The distributions on either side of the perfect class differed, however. At p level only perfect and multiple-flyback attacks were observed, some of them being very long, as discussed above. At mf and f levels, multiple-flyback attacks were still the dominating type for tenuto and détaché, while the martellato strokes were played with a pronounced rate of prolonged-period attacks. For the second subject, being more prone to high bow pressures,[11] almost all attacks were of the prolonged period type at f level, also for tenuto and détaché bowing.

The analogy between a martellato stroke and a consonant in an initial position in speech is evident. Such a ''transient'' in speech with a typical duration of 70 ms, is, however, slightly longer than most pre-Helmholtz transients in martellato.

Some notes are easier to start than others. The second of the two notes played in two successive up-bows [see Fig. 5(a)] showed markedly shorter attack durations, suggesting that this note was particularly easy to start. Both players played this note with a perfect attack in 12 successive recordings. The explanation would be that the Helmholtz corner is already circulating on the string in the same direction as the second bow stroke will induce. Accordingly, no phase reversal of the string motion needs to take place, and the frictional forces during the attack of the second note will be within the allowed range for a perfect attack in a larger number of cases.

b. E string. The attack durations for the E string were distributed within the same limits as for the G string (<50 ms, prolonged periods; <90 ms, multiple flyback), but with a clear shift towards prolonged periods. This was in particular the case for the martellato strokes for which the multiple-flyback attacks gave way for perfect attacks at p level, and where essentially all attacks were found on the prolonged side at mf and f levels. The peak in the pooled martello distribution ($p+mf+f$) was located at 10–20 ms of prolongation instead of at zero duration (perfect attack), which was the case for the G string.

Possibly, the explanation could be sought in the need for safety margins in bowing. String players often attack the open top string with excess bow force (and/or lower velocity) in order to establish a safety margin against long multiple-flyback attacks. Thin strings, like the top E string on the violin, are much more inclined to ''whistling'' (lasting multiple-flyback motion) than thicker strings such as the low G string. The reason is that the reflections returning to the bow are better defined on a thin string. The need for larger safety margins in the playing of the open string might have infected the bowing of the stopped E string as well, although much less needed. The kinks are now reflected at the soft finger pad and loose in definition, and an excessive bow pressure only results in prolonged periods, as observed.

A comparison between the accepted attacks for the G and the E string, respectively, shows that fewer periods were spent before the triggering of the Helmholtz motion when playing on the G string. As the acceptance limits were the same in absolute terms, the number of periods in accepted attacks was only 30% (196 : 660 Hz) for the G string compared to the E string. An extension of this result to the lower string instruments, assuming an approximately constant upper limit for the attack duration in absolute terms (50 and 90 ms), would imply a need for very high precision in the control of the bowing. In these terms, an acceptable attack on the lowest string on the cello and double bass would correspond to a few nominal periods only (3–6 periods for cello; 2–4 periods for double bass).

2. Beethoven, Bach, and Bizet

As a complement to the simple tune, the first subject was asked to perform some music from the violin literature of his own choosing, representative of the three types of bowing. Excerpts from the following pieces were selected; Beethoven violin concerto (*tenuto*), a Bach prelude (*détaché*), and L'Arlésienne suite by Bizet (*martellato*), all performed on the G string [see Fig. 5(b)–(d)].

The distributions of attack durations for these excerpts were rather similar to the corresponding versions of the simple tune, taking into account that the Bizet example was performed fairly loud (about f), and the Beethoven and Bach examples much softer (mf) (cf. Figs. 6 and 7). This result suggests that the particular choice of music, given a certain dynamic level and bowing style, does not affect the distribution of the durations of the pre-Helmholtz transients dramatically. Within the ''archetype'' distributions, variations will, of course, occur, reflecting the mood and characteristics of the piece among other things.

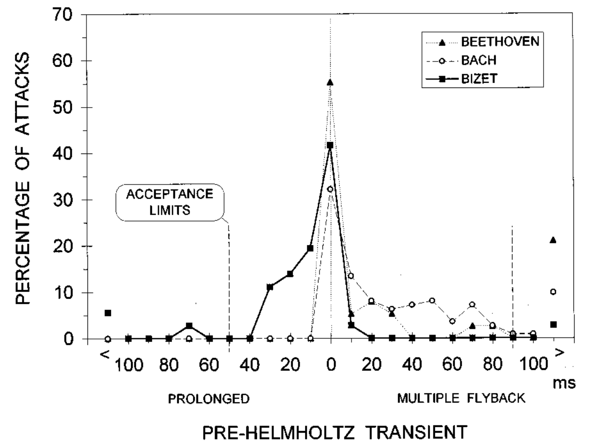

FIG. 7. Distributions of the durations of pre-Helmholtz transients in performances of excerpts from the classical violin literature representing different bowing styles, including theme from Beethoven's violin concerto, *tenuto* (39 attacks), excerpt from Preludio V from Das Wohltemperierte Klavier by J. S. Bach, *détaché* (112 attacks), and theme from L'Arlésienne suite by Bizet, *martellato* (36 attacks). All examples played on the G string.

3. Spiccato, sautillé, and ricochet

Other types of bowings were tried as well, including *spiccato* (''cut off,'' with a springing bow) in eighth notes, a faster version (*sautillé*) in sixteenth notes, and a very rhythmic *ricochet* (''rebounding'') bowing *à* la Wilhelm Tell overture, combining several bouncing strokes in one direction [see Fig. 5(e)].

In spiccato, very few multiple-flyback attacks were observed (see Fig. 8). The prolonged-period attacks stayed well within the 50-ms limit found earlier, with few exceptions. The perfect attacks were particularly numerous for spiccato on one string (played in groups of four with three consecutive notes of the same pitch) reaching 64%. As soon as a second string was interleaved every other note, the ''perfect'' rate lowered to 33%.

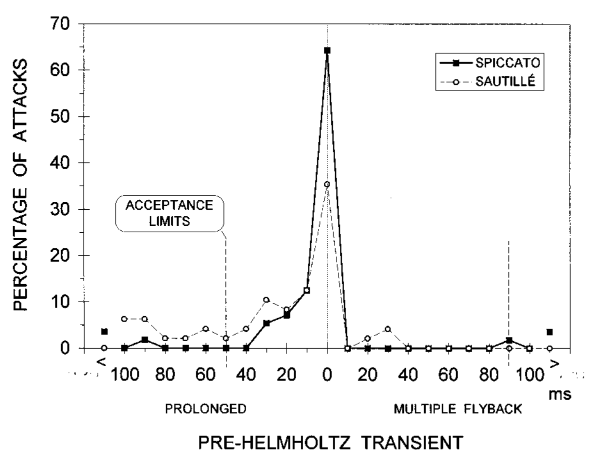

FIG. 8. Distributions of the durations of pre-Helmholtz transients in *spiccato* on one string (56 attacks), and *sautillé* (48 attacks), both examples played on the G string.

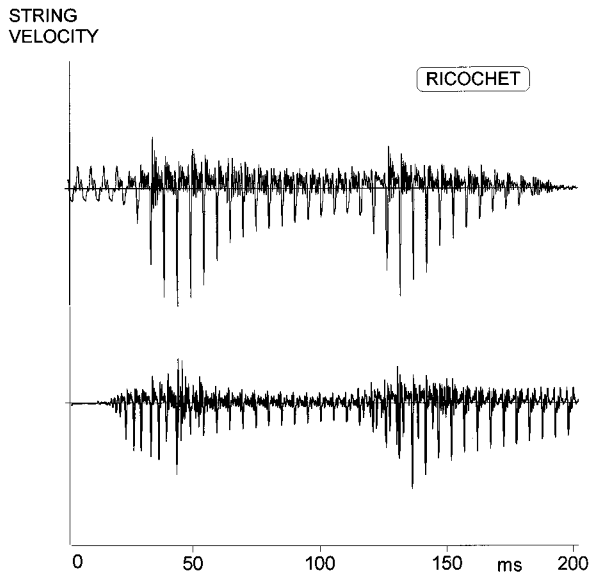

FIG. 9. Examples of excellent (*top*) and poor attacks (*bottom*) of sixteenth notes in the ricochet example, showing the string velocity close to the bowing point. Note that in the upper example a decaying string vibration (mainly fundamental) is present at the onset of the first note.

Sautillé bowing gave a higher rate of long prolonged-period attacks, up to 100-ms duration, and a ''perfect'' rate of 35% (see Fig. 8). Short multiple-flyback attacks occurred as well, altogether giving a much less clear perception of each individual note compared to the spiccato.

The rapid ricochet bowing gave no multiple flybacks, a high rate of perfect attacks (45%), and the main part of the prolonged-period attacks within the 50 ms limit. A certain amount of longer prolonged attacks, up to 100 ms, was observed as well. For a sixteenth note, which in this example lasted between 70 and 100 ms (corresponding to 14–20 nominal periods only), this means that a major part of the note was spent on the pre-Helmholtz transient. This ''failure'' occurred in almost 20% of the sixteenth notes in the ricochet example. Examples of excellent and poor ricochet attacks are shown in Fig. 9.

In addition to the results reported above, the playing test offered several interesting comparisons between the actual string motion and the perceived tone quality, which would motivate a larger separate study.

III. CONCLUSIONS

The study shows that string players are very sensitive to the quality of bowed attacks, and that they agree in their preferences. A narrow span defines the allowed duration of transients in acceptable attacks. For the main parameter investigated, that is, the duration of the aperiodic part of the attack before the triggering of the Helmholtz motion (the *pre-Helmholtz transient*), the acceptance limits were 50 ms (prolonged periods) and 90 ms (multiple flyback). In terms of nominal periods these limits correspond to 10 and 18 periods, respectively (violin, open G string). Attacks with prolonged periods are perceived as being ''choked/creaky,'' while multiple-flyback attacks are characterized as ''loose/slipping.''

The same approximate limits in absolute terms (ms) were obtained for ''viola'' attacks (obtained from transposed violin attacks), the number of nominal periods now being reduced to only 7 for prolonged-period attacks, and 12 for multiple-flyback attacks.

An analysis of variance using a mixed model with subjects as a random factor showed a high reliability in the data, which indicates that the results of the listening test can be generalized to represent the opinion of a large population of string students and professionals.

The acceptance limits were first obtained in a listening test in which advanced string students and professionals judged the acceptance of recorded attacks with reference to a neutral attack. Following, a playing test with two professional violinists verified that the same approximate limits apply to the pre-Helmholtz transients in normal violin playing as well. As a rule of thumb, only 20%–50% of the notes in a performance can be expected to start with a perfect attack, showing a periodic Helmholtz triggering from the very beginning. On the other hand, as much as 80%–90% of the attacks will stay within the acceptance limits (50/90 ms).

A closer examination of the data indicates that several parameters other than the duration of the pre-Helmholtz transient play important roles in the perception of bowed attacks.

Accents. Any initial accent would shift the perceived character in the direction of ''choking the string.'' This tendency is, however, probably strongly related to the musical context. In the listening test the attacks were judged with reference to a ''neutral'' context, like when practicing a scale.

Amplitude buildup time. A low bow acceleration which results in a slow buildup to final ''steady-state'' amplitude, after the Helmholtz triggering has been established, adds to the impression of the string being choked.

Nominal fundamental frequency. The results of the listening test as well as the playing test suggest that the acceptance limits for the duration of the pre-Helmholtz transient is about equal for different fundamental frequencies when expressed in absolute terms (ms). In the listening test the fundamental frequencies were limited to 196 and 130 Hz (open violin G string and ''viola'' C string), while a larger range was sampled in the playing test (196–940 Hz). If this finding was verified in a formal study, it would mean that instruments operating in a lower fundamental frequency range (viola, cello, double bass) cannot afford as many periods as the violin before reaching Helmholtz triggering. This would imply a narrower range in bowing parameters for these instruments, closer to the perfect conditions.

It may well be, however, that the upper frequency limit in the spectra and the rate at which the spectral changes take place—parameters which both are dependent on the pitch range—play a role for the perceived attack quality. A hint in this direction is found in Fig. 2 where the rejected attacks (below the acceptance threshold) were rated lower for the violin than for the ''viola.'' This result was verified in a smaller preliminary test, in which the fundamental frequency of series B was lowered to 65 Hz, comparable to the open C string of a cello. The reason may be that a poor attack sounds less erroneous when the spectrum changes more slowly. A consequence of that would be that bowing errors are less dramatic for the lower-pitched bowed instruments than for the violin. A dedicated study would be needed to settle these questions.

Pre-Helmholtz transients with durations well outside the limits found in this study certainly do occur in professional performances. Although all string players spend a considerable part of their studies learning to master the bow-string control, not all professionals are able to perform attacks at the same quality level. Nevertheless, the ideal remains the same, a perfect attack with periodic Helmholtz triggering from the very start. Another aspect of the pre-Helmholtz transient is the occasional musical desire to create tone colors outside of the *beau idéal*. For instance, a series of soloistic sforzandi may consist of prolonged periods only, while a soft (''from nothing'') entrance of a string section may show several seconds of nothing but multiple-flyback attacks.

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